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AUTHOR(S): Daniel W. Hudgings and Andrew J. Jason

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LOS ALAMOS SCIENTIFIC LABORATORY
Post Office Box 1663 Los Alamos, New Mexico 87545
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INJECTION SYSTEM FOR THE PROTON STORAGE RING AT LASL*)

Daniel W. Hudgings and Andrew J. Jason

Los Alamos Scientific Laboratory, Los Alamos, NM 87545 USA

ABSTRACT

The Proton Storage Ring at LAMPF will accumulate a high current of 800-MeV protons by multiturn charge-changing injection. An 800-MeV neutral hydrogen atomic beam, formed by field ionization of H- ions in a 1.8 T transverse magnetic field, will be stripped to protons by a carbon foil. To minimize peak proton current on the foil, the beam orbit will be deformed so that the edge of the beam grazes the edge of the foil. As the beam diameter grows, the orbit perturbation is decreased, vanishing at the end of the accumulation cycle. The hardware requirements are simple. Single-turn orbit deformation magnets are pulsed to peak field and switched across power dissipation circuits that control the field decay rate.

Stripping foil requirements and a method of calculating the desired orbit deformation are decribed.

1. INTRODUCTION

High-current 800-MeV proton beams will be accumulated in the Proton Storage Ring (PSR) at LASL by multiturn charge-changing injection of H^- ions from the LAMPF linac. Two modes of operation will be used: a short-bunch mode in which six bunches of 10^{11} protons are accumulated in 108 μs, and a long-bunch mode in which a 270-ns bunch of 5.2×10^{13} protons is accumulated in 750 μs[1]. Peak current in the long-bunch mode is 46.3 A, with the injection and extraction cycle repeated at a 12-pps rate.

A chopper in the low-energy transport between the 750-kV injector and Alvarez linac section at LAMPF prepares the beam in the required temporal format[1]. After acceleration to 800 MeV the beam is switched into beam line D and deflected from line D into the PSR injection line by a kicker magnet and skewed dipole. Figure 1 shows the rest of the injection system in summary form. Another skewed dipole directs the beam approximately collinearly to the circulating beam in the injection straight section of the PSR. Achromatic transport in the injection line is achieved by focusing elements that cause cancellation of the dispersion of the two bend magnets. Both the horizontal and vertical phase ellipses rotate significantly in the drift space between the third quadrupole and second skewed dipole. This permits us to remove the nominally Gaussian edges of the injected beam to the 3-σ level by stripping on a series of foil apertures. The unwanted stripped beam is deflected into a beam dump by the skewed magnet. Programmed steering magnets adjust the ion beam trajectory through a stripping magnet (which converts H^- to H^0) onto the stripping foil (which converts H^0 to H^+). Unstripped H^0 beam drifts through a dipole magnet into a beam dump. Programmed bump magnets in the PSR radially deform the closed orbit to control the profile of the accumulating beam.

2. CHARGE CHANGING INJECTION

A novel two-step charge-changing scheme will be used for injection into the PSR[2]. Figure 2 shows the 1/e stripping length of 800-MeV H^- ions as a function of magnetic field in the laboratory frame of reference, as measured in a recent experiment at LAMPF[3] and as calculated from the results of Stinson, et al.[4].

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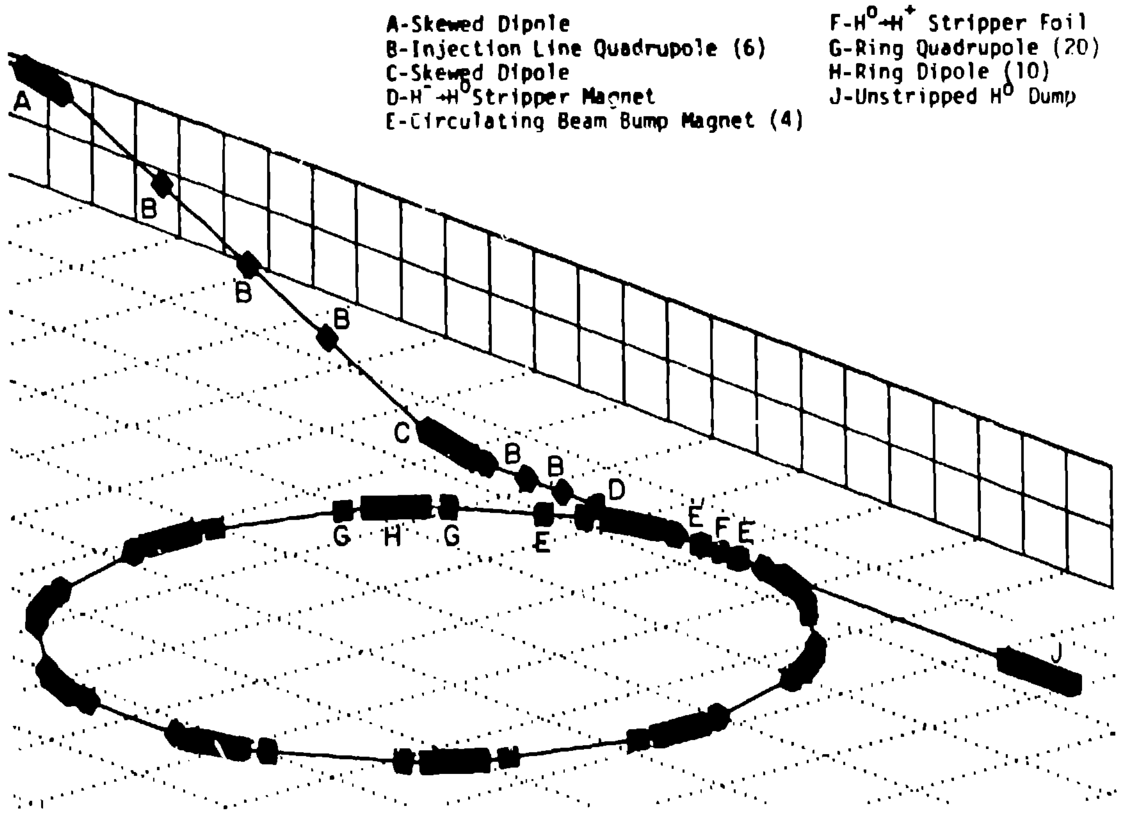

Fig. 1. PSR injection system schematic.

Charge-changing injection is necessary because the accumulation of beam for many (300 to 3000) machine circulation periods requires the brightness of the circulating beam to exceed that of the injected beam. Conventionally, this is done by blending the injected H^- beam and the circulating H^+ beam in a magnetic field and directing them through a stripping foil. Because field stripping of 800-MeV H^- ions is a significant effect for bending radii less than 12.8 m, this method is difficult to implement for the PSR. The ease with which the H^- ion can be Lorentz stripped is a problem in beam transport, but can be used to great advantage. By stripping the H^- ion beam to neutral hydrogen in a strong transverse magnetic field, the beam can be passed unperturbed through a ring dipole and focusing quadrupole to the foil, which then strips it to H^+. The H^0 beam can be "painted" across the stripping foil in the

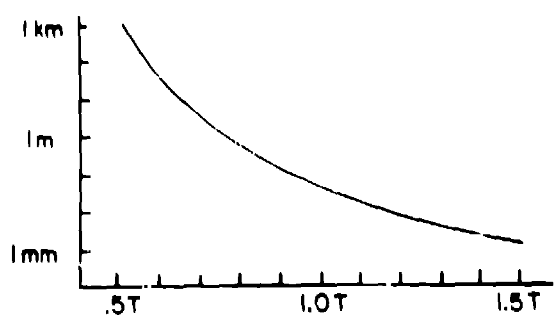

Fig. 2. 1/e Lorentz stripping length H^- to H^0 for 800-MeV H^- ions as function of magnetic field.

vertical direction during the injection cycle by pulsed steering magnets that precede the stripping magnet. An increase in beam angular divergence, caused by the stripping process, of < 1.6 mrad was measured in an experiment at LAMPF using a simple dipole magnet[3]. A smaller divergence increase should be achievable using the specially designed magnet intended for the PSR injection system[2].

3. STRIPPING FOIL CONSIDERATIONS

A carbon foil will strip the H^0 beam to protons. The parameters considered in selecting foil thickness were beam emittance growth from multiple scattering in the foil, foil lifetime, stripping efficiency, and the release of radioactive material from the foil. A minimum foil thickness of ~200 $\mu g\ cm^{-2}$ is required for at least 95% stripping efficiency, to limit the beam absorbed in the neutral beam dump to 5 μA. For this foil thickness the other parameters are acceptable. Less than one part in 10^{12} of the circulating beam is lost because of elastic scattering. Inelastic scattering results in losses of ~30 nA in the region immediately downstream of the foil. Foil activation in long-pulse service is summarized in Table 1.

Foil heating rate is determined by the circulating beam-current density on the foil. The characteristic time for temperature decrease by thermal radiation, the only significant heat-loss mechanism, is several times the 750-μs beam accumulation period. Thus the foil's peak temperature is largely independent of thickness, and depends only on its specific heat, differential stopping power, and the beam-current density. For the injection programming scheme described below, the peak foil temperature should be ~1200°C.

Radiation damage may be the key factor limiting foil lifetime. Damage estimates predict minimum lifetimes of hours for suitably prepared foils. Foils will be mounted on frames in a device that permits automatic and rapid replacement of damaged units.

4. PHASE-SPACE CONTROL

An advantage of multiturn beam accumulation is that the transverse phase-space distribution of the beam can be controlled by steering the injected beam and the circulating beam on the stripping foil.

Injected beam is accumulated on the surface of the circulating beam. This has the advantage of zero closed orbit perturbation at the end of the injection cycle, when the accumulated beam and resultant tune shifts are greatest. The foil intersects only a fraction of the X-X' phase-space projection of the beam and thus is struck by each stored proton only in a fraction of its circuits around the ring. This process is illustrated in Fig. 3, which shows the X-X' phase space occupied by the beam near the beginning and at the end of the accumulation period.

Beam accumulation can be described by a Green's function method. Assuming an irrational

Table 1

Carbon Stripping Foil Activation for 2-hour Service

Isotope	Half-life	2-hr. Activation
C^{11}	20 min	0.37 Ci
H^3	12.3 yrs	3.2 μCi
Be^7	53.4 days	130 μCi

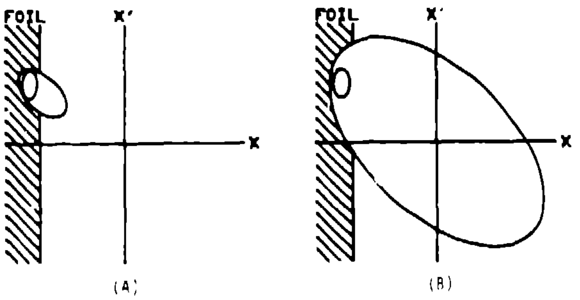

Fig. 3. Beam Accumulation:
(A) Near beginning of accumulation period with circulating beam displaced toward foil.
(B) End of accumulation period, circulating beam centered on unperturbed equilibrium.

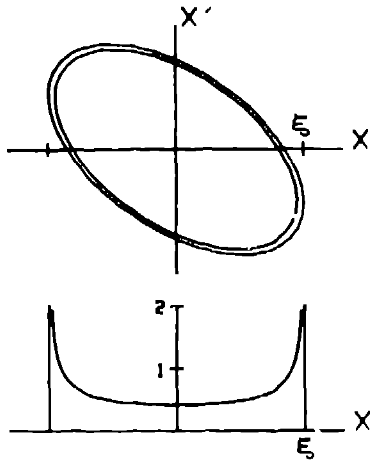

Fig. 4. Green's function for beam accumulation.

horizontal tune so that spatially impulsive injection distributes beam uniformly into a narrow annulus in the X-X' projection of the beam phase space, the appropriate Green's function is

$$G(X,\xi) = (1/\pi)(\xi^2 - X^2)^{-1/2}\,[H(\xi - X) - H(-\xi - X)] \qquad (1)$$

where H is the Heaviside step function and the variable ξ is the x-component of the injection radius relative to the beam axis. This is illustrated in Fig. 4. The beam distribution shown in Fig. 5 is obtained for

$$\xi(t) = X_{max}\ (1-t/t_{max})^{1/2}\ H(t)\ H(t_{max} - t) \qquad (2)$$

where X_{max} is the half-width of the fully accumulated beam and t_{max} is the accumulation time. Rapid injected beam movement near the center of accumulated beam, as is the case for Eq. 2, is necessary to avoid beam pileup. This type of analysis has been extended to bivariate distributions and finite injection spot size.

Beam profile also can be controlled by programming the vertical size of the injected beam spot on the stripping foil, which, along with the bump magnet system, permits simultaneous control of both transverse components of the distribution. This function is provided by the final quadrupole in the PSR injection line.

Fig. 5. Beam-bumping program (A) produces beam distribution (B).

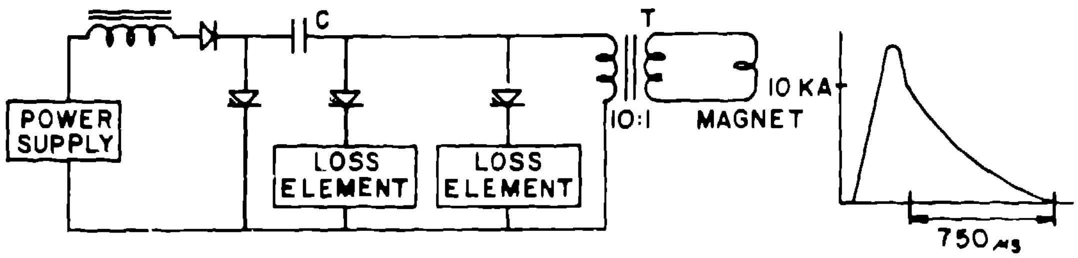

Fig. 6. Pulsed power supply for bump magnets. Loss elements are switched in after peak of field is passed, to control rate of field decay. Thyristor trigger elements are not shown.

Figure 6 shows a schematic of a pulsed power supply for driving the single-turn bump magnets that deform the closed orbit. The energy stored in capacitor C is switched through transformer T into the field of the magnet. Energy dissipation elements are switched across the primary side of the transformer to control the rate of field decay.

The transformer, which permits switch operation at a practical impedance level, is a low inductance type developed for controlling a plasma pinch device[5]. The switches are thyristors. For energy dissipation elements we have used resistors in series with zener diodes or zener diode/power transistor combinations. A tenth-scale model using an active feedback circuit and power transistors for the dissipative element was tested successfully, but no full-scale actively regulated circuit has yet been tried.

5. CONCLUSION

We have designed an injection system for the PSR that utilizes the best features of a unique asset: an 800-MeV H^- ion injector. The high beam energy makes possible neutral beam injection. Neutral injection and the low emittance of the injected beam permit multiturn beam accumulation with low loss and precise control of the circulating beam profile. The ability to change easily the beam distribution function in the PSR should make it an attractive test bed for investigating high-current accumulation in a proton storage ring.

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